

Hierarchical build-up of galactic bulges and the merging rate of supermassive binary black holes

Martin G. Haehnelt[†] §

[†] Institute of Astronomy, Madingley Road, CB3 0HA, Cambridge, UK

Abstract. The hierarchical build-up of galactic bulges should lead to the build-up of present-day supermassive black holes by a mixture of gas accretion and merging of supermassive black holes. The tight relation between black hole mass and stellar velocity dispersion is thereby a strong argument that the supermassive black holes in merging galactic bulges do indeed merge. Otherwise the ejection of supermassive black holes by gravitational slingshot would lead to excessive scatter in this relation. At high redshift the coalescence of massive black hole binaries is likely to be driven by the accretion of gas in the major mergers signposted by optically bright QSO activity. If massive black holes only form efficiently by direct collapse of gas in deep galactic potential wells with $v_c \gtrsim 100 \text{ km s}^{-1}$ as postulated in the model of Kauffmann & Haehnelt (2000) LISA expects to see event rates from the merging of massive binary black holes of about $0.1\text{--}1 \text{ yr}^{-1}$ spread over the redshift range $0 \leq z \leq 5$. If, however, the hierarchical build-up of supermassive black holes extends to pre-galactic structures with significantly shallower potential wells event rates may be as high as $10\text{--}100 \text{ yr}^{-1}$ and will be dominated by events from redshift $z \gtrsim 5$.

PACS numbers: 04.30.Db, 04.70.Bw, 98.62.Js

1. Hierarchical build-up of supermassive black holes and galactic bulges

According to the standard paradigm of structure formation in the Universe, galaxies merge frequently as their dark matter halos assemble. This process has been modeled extensively using Monte-Carlo realizations which include simple prescriptions to describe gas cooling, star formation, supernova feedback and merging rates of galaxies (see e.g. Kauffmann et al. 1999 for a recent account). Kauffmann & Haehnelt (KH2000) introduced a “unified” model for the evolution of galaxies and quasars in a cold dark matter (CDM) dominated Universe. In the model of KH2000, spheroids form when two galaxies of comparable mass merge. The resulting gas accretion onto the merging black holes leads to QSO activity which lasts for a few times 10^7 yr . The model of KH2000 is able to reproduce a wide variety of galaxy and QSO properties like the galaxy/QSO luminosity function and its evolution with redshift, host galaxy luminosities, the $M_\bullet\text{--}\sigma_*$ relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Haehnelt & Kauffmann 2000), and the clustering properties of galaxies and QSOs (Kauffmann & Haehnelt 2002). The wealth of observational constraints gives some

§ haehnelt@ast.cam.ac.uk

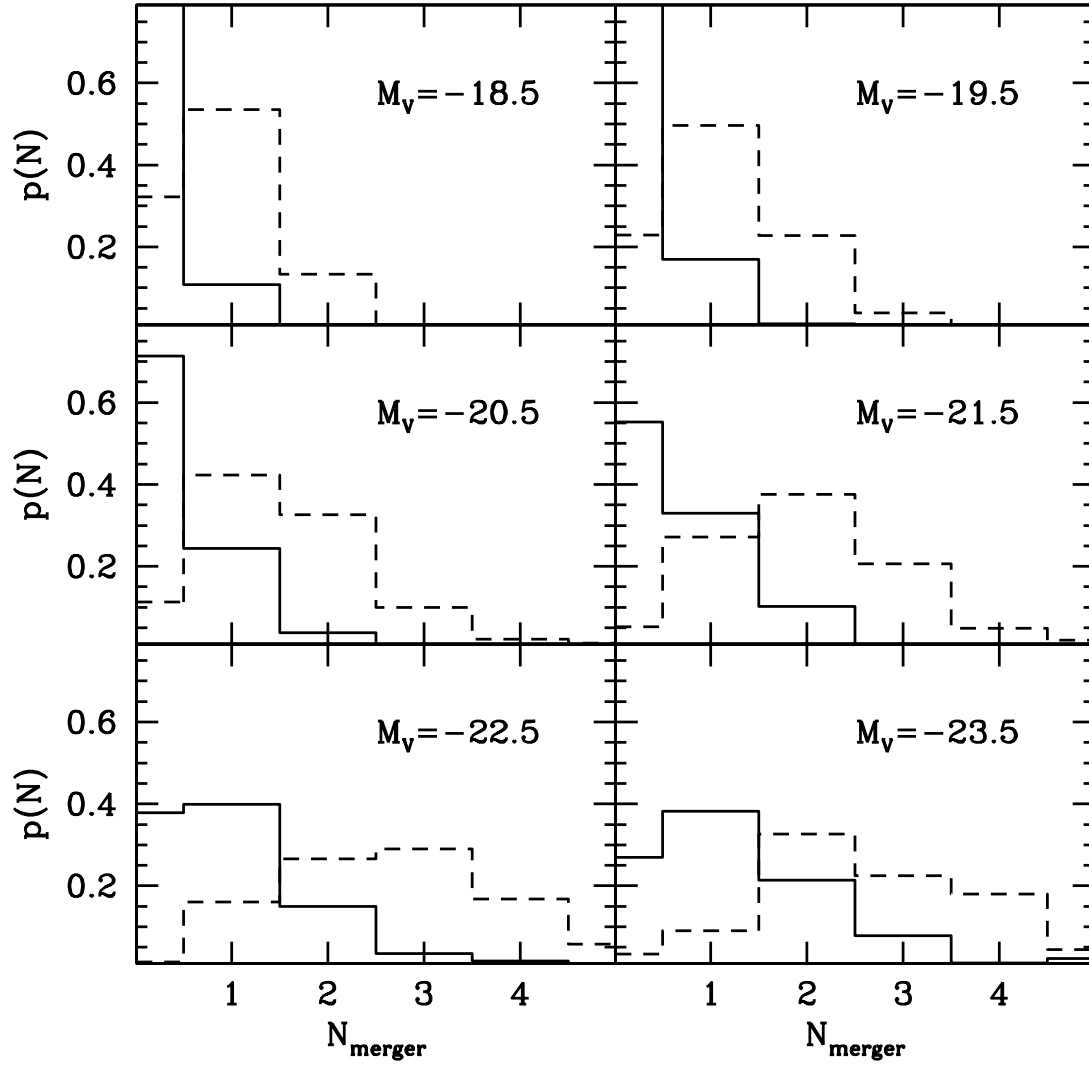


Figure 1. The probability distribution of the number number of mergers expected to lead to the formation of massive binary black holes with mass ratios > 0.3 in galactic bulges with different V-band luminosities. The dashed curves show the total number, while the solid curves show the number after the last major gas accretion event (Haehnelt& Kauffmann 2002).

confidence that the model gives a realistic account of the expected merging rate of galactic bulges and the gas accretion history of the central supermassive black holes in typical nearby bright galaxies despite the simplicity with which relevant physical and dynamical processes are modeled.

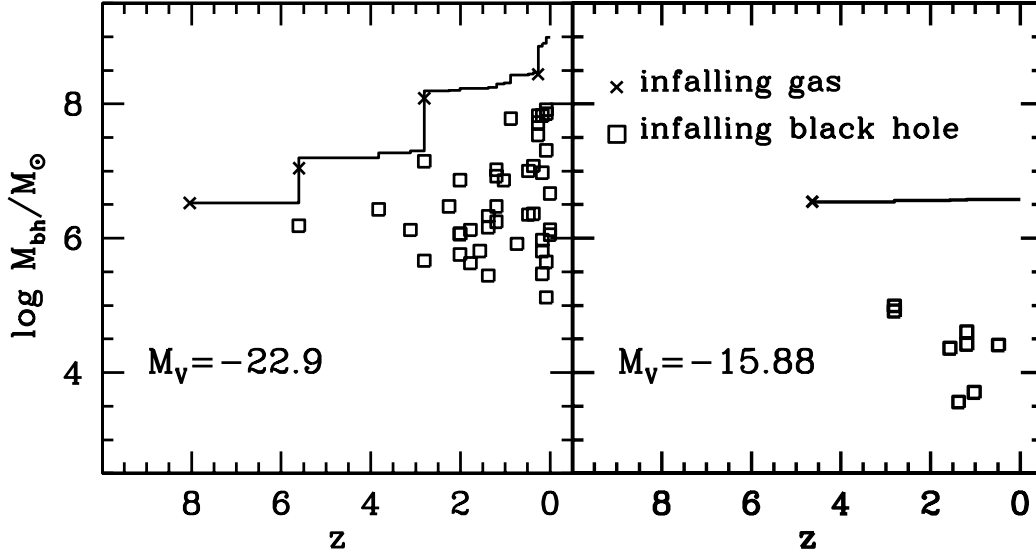


Figure 2. Typical accretion/merging history of the central black hole in a bright (left) and faint (right) galactic bulge in the model of Kauffmann & Haehnelt (2000). Crosses denote gas infall during major galaxy mergers and squares denote the infall of black holes.

2. Supermassive binaries in present-day galactic bulges

The frequent merging of galaxies which each contain one or more black holes will lead to the occurrence of multiple black holes. When two galaxies merge, the smaller galaxy will sink to the centre of the merger remnant because of dynamical friction. The outer regions of the infalling galaxy will be gradually tidally stripped in the process. If two galaxies with roughly equal mass merge, a binary black hole will form within a few dynamical times (e.g. Milosavljević & Merritt 2001). The subsequent evolution of the supermassive binary once the binary is hard (*i.e.* its orbital velocity is comparable to the velocity dispersion of the stars) has been first discussed by Begelman, Blandford & Rees (1980). The binary is expected to harden either by gravitational sling-shot ejection of stars (*e.g.* Quinlan 1996) or by the accretion of gas onto the binary system (Armitage & Natarajan 2002). The timescale for the ejection of stars to cause the binary to harden may exceed the Hubble time in bright galaxies (Yu 2002). This raises the possibility of triple interactions of supermassive black holes which may lead to the ejection of black holes from the centre by gravitational slingshot (Saslaw, Valtonen & Aarseth 1974). The frequent merging predicted by hierarchical galaxy formation models is then inconsistent with the observed tight $M_{\bullet}-\sigma_{*}$ relation unless the gas accretion during phases of QSO activity merges black holes efficiently. The dashed lines in Fig. 1 shows the predicted number of major mergers ($m_{\text{sec}}/m_{\text{prim}} > 0.3$). Typical bright elliptical galaxies are expected to undergo several major mergers. If the merging timescale of supermassive binary black holes is longer than the Hubble time, a binary should be ejected

in a large fraction of bright elliptical galaxies. This would appear to conflict with the fact that black holes are observed in all nearby bright elliptical galaxies and with the tightness of the observed $M_\bullet - \sigma_*$ relation (Ferrarese & Merritt 2000, Gebhardt et al. 2000). The solid curve shows instead the predicted number of major mergers after the last accretion event in which the mass of accreted gas exceeded the sum of the masses of the two black holes in the binary system. The median number of mergers since this event is significantly smaller and ranges from zero in faint galaxies to one in bright galaxies. If the supermassive black holes do indeed merge during gas-rich accretion events, the fraction of elliptical galaxies containing large mass ratio binary black holes will not be larger than 10% in faint ellipticals and 40% in brighter objects. The fraction of galaxies with a third massive “intruder” ranges from 0 to 20 percent. Binary black hole ejection will then only occur in a small fraction of only the brightest galaxies (Haehnelt & Kauffmann 2002). Figure 2 shows typical merging/ accretion histories of the central black hole in a bright and faint galactic bulge. Note that the good agreement between the present-day black hole mass density and that inferred to be accreted using Soltan’s argument (Soltan 1982) does not leave much room for growth of black holes other than by merging and infall of gas during phases of optically bright QSO activity (Yu & Tremaine 2002). The crosses in Fig. 3 show the black hole mass function of the model of HK2000 while the solid curve shows the black hole mass function in early-type galaxies as determined by Yu & Tremaine (2002) using the galaxy sample of Bernardi et al. 2002. Note that the result by Yu & Tremaine (2002) does not take into account black holes in the bulges of spiral galaxies. The discrepancy with the model at the low mass end is thus expected. In the model of KH2000 the efficiency of funneling cold gas to the centre of the galaxy is a strong function of the depth of the potential well and black holes initially form from collapse of the cold gas in potential wells with circular velocity $v_c \gtrsim 100 \text{ km s}^{-1}$. This leads to rather massive effective “seed” black holes and the drop of the black hole mass function at masses $\lesssim 10^7 M_\odot$ in Fig.3.

3. Merging rates of galactic bulges in the KH2000 model

For a population of merging sources with comoving density of mergers per unit redshift dn_{merge}/dz the all-sky event rate per unit redshift can be written as

$$\begin{aligned} dN_{\text{merge}}/dz/dt &= 4\pi R(z)^2 c \, dn_{\text{merge}}/dz \\ &\approx 0.08 (n_{\text{merge}}/10^{-3} \text{Mpc}^{-3}) r(z)^2 \text{ yr}^{-1} \end{aligned}$$

where $R(z) = r(z)c/H_0$ and $r(z) = 1/\int (\Omega_m(1+z)^3 + (1 - \Omega_m - \lambda)(1+z)^2 + \lambda dz)$ and $h=0.65$ was assumed. The planned gravitational wave interferometer LISA is expected to detect black hole coalescences with primary black hole masses of $10^6 - 10^7 M_\odot$ and mass ratios as small as 0.01 out to very large redshifts (e.g. Bender these proceedings). Figure 4 shows the merging rates of galactic bulges expected to form massive binary black holes with the mass of the primary in this range for different mass ratios. Note, however, that in order to interpret

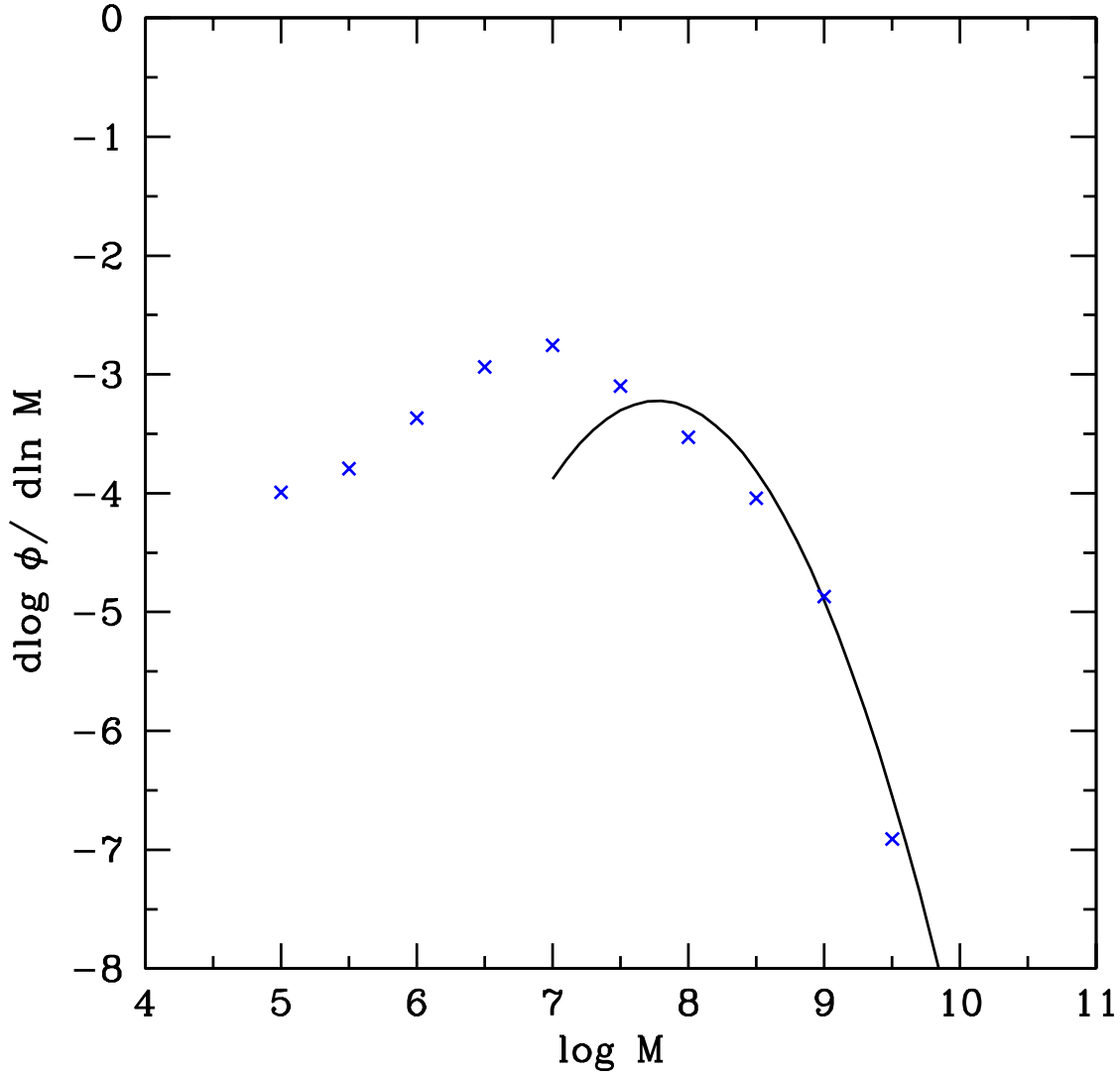


Figure 3. Crosses show the present-day black hole mass function in the model of Haehnelt & Kauffmann (2000). The solid curve shows the black hole function in early-type galaxies inferred by Yu & Tremaine (2002) from the galaxy sample of Bernardi et al. (2002). Note that the mass function of Yu & Tremaine does not account for black holes in the bulges of spiral galaxies.

these as potential LISA event rates one has to assume that these binaries do neither get “hung-up” (Begelman, Blandford & Rees 1980; Milosavljević these proceedings) nor are ejected by gravitational sling-shot (Saslaw, Valtonen & Aarseth 1974). The total predicted rate for the mass range shown in Figure 4 is 0.3 yr^{-1} spread over the redshift range $0 \leq z \leq 5$. Including events with larger primary mass and smaller mass ratios will increase this rate to about 1 yr^{-1} . Note, however, again that the specific assumptions made in KH2000 on how “seed” black holes form lead to a rapidly declining mass function below $10^7 M_{\odot}$. These assumptions were motivated by the rather large overall efficiency with which black holes in galactic bulges have

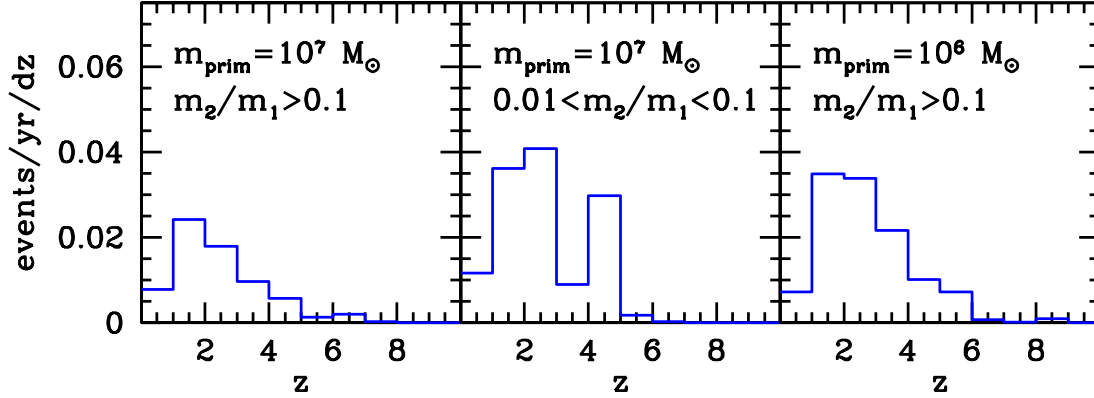


Figure 4. Merger rate of galactic bulges expected to form massive binary black holes for a range of primary black hole masses and mass ratios relevant to LISA in the model of KH2000.

formed. The black hole mass is about 0.1 percent of the stellar mass. Currently little is known observationally about the mass function below $10^6 M_\odot$. Recent claims of the detection of intermediate mass black holes in two globular clusters are controversial (Gerssen et al. 2002, Gebhardt et al. 2002). The same holds for the interpretation of the ultraluminous compact X-ray sources as intermediate mass black holes (e.g. King et al. 2001). Nevertheless the evolution of a dense stellar cluster in the collisional regime and Eddington limited accretion onto stellar mass black holes are plausible mechanism for the formation of a population of intermediate mass black holes albeit almost certainly with a smaller efficiency (Begelman & Rees 1978; Rees 1984; Madau & Rees 2000, Portegies Zwart & McMillan 2002). In the next section we will discuss simple estimates for the expected event rates of the hierarchical build-up of supermassive black holes from stellar or intermediate mass seed black holes in pre-galactic structures.

4. Build-up of black holes in hierarchical merging pre-galactic structures

The typical mass of the DM halo hosting a bulge with a $10^7 M_\odot$ black hole should be about $10^{12} M_\odot$. The hierarchical build-up of galaxies is expected, however, to start at much smaller masses. The total merging rate of these small DM haloes is about $10 (M_{\text{halo}}/10^{11} M_\odot)^{-1} \text{yr}^{-1}$. If mergers of small haloes at high redshift lead to detectable black hole coalescences the corresponding event rates will be much larger than those discussed in the last section (Haehnelt 1994, Haehnelt 1998, Menou et al. 2001). Unfortunately we do not have much of a handle on the mass function and assembly history of black holes in these haloes (see Volonteri et al. 2002 for a first attempt to model these in detail). We can nevertheless try to get at least an upper limit on the expected event rates which is consistent with the observed present-day black hole mass density. Yu and Tremaine (2002) obtain $\rho_{\text{bh}} = 2.5 \times 10^5 M_\odot \text{Mpc}^{-3}$ with a mean black hole mass of $\sim 10^8 M_\odot$ (see also Aller & Richstone 2002). If we assume that these build up solely by equal mass mergers of black holes with a minimum

mass M_{\min} this would correspond to an event rate of $200 (M_{\min}/10^5 M_{\odot})^{-1} \text{ yr}^{-1}$. Obviously this is overly optimistic as we know that black holes must have accreted a considerable fraction of their mass when their masses were already larger than $10^7 M_{\odot}$ in order to produce the light emitted by optically bright QSOs. The usual caveat that massive black hole binaries may not actually merge is obviously also still valid. A merger rate of 10 yr^{-1} may be a more realistic estimate of the coalescence rate in case intermediate black holes were indeed forming in dark matter haloes with $v_c < 100 \text{ km s}^{-1}$. Note also, that such frequent merging of black holes in low mass DM haloes would require a steep black hole mass function. Most of these events would occur at $z \gtrsim 5$.

5. Conclusion

The frequent merging of galactic bulges expected in hierarchical models of structure formation together with the fact that all galactic bulges appear to contain supermassive black holes makes the formation of supermassive binary black holes inevitable. The tightness of the observed relation between black hole mass and stellar velocity dispersion leaves thereby little room for hung-up and subsequently ejected binaries giving reason for some optimism that these binaries do generally coalesce within a Hubble time. The merging rate of galactic bulges expected to form massive binary black holes in the range of primary black hole masses and mass ratios to which LISA will be sensitive is $0.1\text{-}1 \text{ yr}^{-1}$ if massive black holes only form efficiently by direct collapse of gas in deep galactic potential wells with $v_c \gtrsim 100 \text{ km s}^{-1}$, but may be as large as $10\text{-}100 \text{ yr}^{-1}$ if the hierarchical build-up of supermassive black holes extends to pre-galactic structures with significantly shallower potential wells.

Acknowledgments

I am grateful to my collaborator Guinevere Kauffmann for permission to present results of our joint research.

References

- Aller M.C., Richstone D.O., 2002, AJ, in press, astro-ph/0210573
- Armitage P., Natarajan P., 2002, ApJ, 567, L9
- Begelman M., Blandford R., Rees M.J., 1980, Nature, 287, 307
- Begelman M., Rees M.J., 1978, MNRAS, 175, 847 307
- Bernardi M. et al, 2002, AJ in press, astro-ph/0110344 307
- Ferrarese L., Merritt D., 2000, ApJ, 539, L9
- Gebhardt K., Bender R. Bower G., Dressler A., Faber S.M., Filipenko A.V., Green R., Grillmair C., Ho L.C., Kormendy J., Lauer T.R., Magorrian J., Pinkney J., Richstone D., & Tremaine S., 2000, ApJ, 539, L13
- Gebhardt K., Rich R.M., Ho L.C., 2002, ApJ, 578, L41
- Gerssen J., van der Marel R.P., Gebhardt K., Guhathakurta P., Peterson R., Pryor C., 2002, astro-ph/0209315 and astro-ph/0210158
- Haehnelt M.G., 1994, MNRAS, 269, 199
- Haehnelt M.G., 1998, in AIP conference Proceedings 456: Second International LISA Symposium, ed. W.M. Folkner, p. 45

- Haehnelt M.G., Kauffmann G., 2000, MNRAS, 318, L35 (HK2000)
- Haehnelt M.G., Kauffmann G., 2002, MNRAS, 336, L61
- Kauffmann G., Colberg J. M., Diaferio A., White S.D.M., 1999, MNRAS, 303, 188
- Kauffmann G., Haehnelt M.G., 2000, MNRAS, 311, 576 (KH2000)
- Kauffmann G., Haehnelt M.G., 2002, MNRAS, 332, 529
- King A. R., Davies M. B., Ward M. J., Fabbiano G., Elvis M., 2001, ApJ, 552, L109
- Madau P., Rees M.J., 2001, 511, L27
- Menou K., Haiman Z., Narayanan V.K.. 2001, ApJ, 558,a 535
- Milosavljević, Merritt D., 2001, ApJ, 563, 34
- Portegies Zwart S., McMillan S.L. W, 2002, ApJ, 576, 899
- Rees M.J., 1984, ARAA, 22, 471
- Saslaw W.C., Valtonen M.J., Aarseth S.J., 1974, ApJ, 190, 253
- Soltan A., 1982, MNRAS, 200, 115
- Volonteri M., Haardt F., Madau, P., 2002, ApJ, in press astro-ph/0207276
- Yu Q., Tremaine S., 2002, MNRAS, 335, 695
- Yu Q., 2002, MNRAS, 331, 935